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PERCOLATION AND CAPILLARY MOVEMENTS OF WATER THROUGH SAND PRISMS

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CONTENTS

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Introduction

1. *Synopsis.*—Analysis of groundwater profiles and of lateral movements of water through homogeneous sand beds overlying level, impermeable strata are usually based on the assumption that the horizontal component of velocity at any vertical section is constant and proportional to the slope of the groundwater profile at the section. Analytical methods in common use are little different from those outlined by Dupuit in 1863.

Co-ordinate observations of sand permeabilities and of lateral movements of water through sand prisms under conditions simulating free groundwater flow reveal inconsistencies which suggested this investigation.

On the basis of tests of three grades of sand in a flume 18 ft. long, 12 in. wide, and 34 in. deep, observations of groundwater profiles and rates of seepage flow are generalized in terms of head and depth of flow. Rates of flow through the flume for each grade of sand are represented graphically and a nomographic chart, typical of generalized solutions, is presented. Groundwater profiles for all tests are represented by an empirical formula.

The capillary rise of water in sand is investigated and the laboratory observations are generalized nomographically in a chart which represents an equation of the form $h = \frac{K}{d_H}\left(\frac{1 - P}{P}\right)^n$.

Data on stream paths, velocities, rates of flow, capillary rise, and groundwater profiles were obtained from tests of three grades of sand in a glass-walled flume 41 in. long, 3 in. wide, and 18 in. deep. These data, summarized in charts and tables, are consistent with data obtained from tests in the large flume and in the capillarimeter.

The mean velocity of flow in the capillary zone is about two-thirds of that below the groundwater surface and the quantity of capillary flow can be estimated on the basis of data presented herein.

2. *Acknowledgments.*—This paper is based on a doctoral dissertation by TSUNG-PEI TSUI entitled "An Investigation of Groundwater Movements."[1] The investigation was conducted under the direction of DR. F. T. MAVIS, head of the department of mechanics and hydraulics in the laboratory of the Institute of Hydraulic Research. DEAN F. M. DAWSON is dean of the College of Engineering and PROF. E. W. LANE is associate director in charge of the laboratory of the Institute of Hydraulic Research. The authors are indebted to PROF. J. W. HOWE, associate professor of mechanics and hydraulics who conducted preliminary investigations leading up to this study and offered many helpful suggestions.

3. *Purpose.*—The purpose of the study was:

a. To observe the rate of seepage flow of water through different sand mixtures as a function of total head and depths of flow.

b. To observe the profiles of the hydraulic gradient in rectangular sand prisms made up of different sand mixtures.

c. To determine the capillary rise in sand as a function of grain size, gradation, and porosity of sample.

d. To observe the stream paths and velocity distributions as water flows laterally through sand prisms.

LABORATORY METHODS

4. *Apparatus.*—Three sets of apparatus were used in the investigation: (a) a large flume, approximately 1 ft. wide, 3 ft. deep, and 18 ft. long, for observing apparent groundwater profiles for various combinations of headwater and tailwater depths and corresponding rates of discharge for each of three gradations of sand; (b) a capillarimeter for observing the capillary rise of water in a granular material under static conditions; and (c) a small flume approximately $3\frac{1}{2}$ ft. long, $1\frac{1}{2}$ ft. high, and 3 in. wide with one transparent glass side wall for observing certain details of hydraulic pressure and velocity distributions as water flows laterally through a prism of granular material.

(a) Large Flume

Fig. 1 shows a sketch of the large flume which was constructed of 1 x 12 in. planks with a water-tight lining of galvanized sheet

[1] Submitted in the Department of Mechanics and Hydraulics, University of Iowa, in 1937.

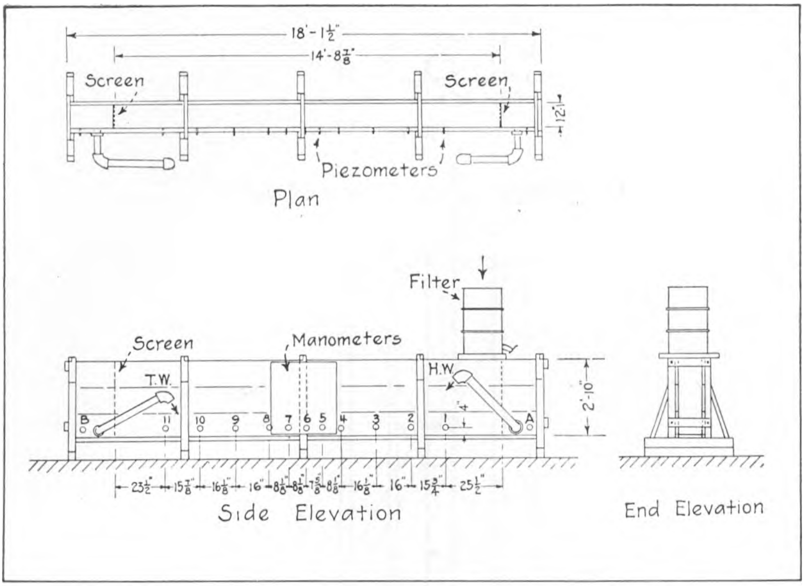

FIG. 1. SKETCH OF APPARATUS—LARGE FLUME.

metal. Piezometric pressures were observed at 13 sections by ½ in. piezometers connected through the left side of the flume 4 in. above the bottom. The pipes projected ½ in. beyond the inside face of the flume lining and were covered with wire cloth. The piezometer nipples were connected by ½ in. rubber tubing to a manometer and all manometer readings were referred to the bottom of the flume as datum.

Wooden gratings constructed across the flume near the upper and lower ends were covered with two layers of No. 20 wire cloth separating the sand prisms from the headwater and tailwater pools respectively. The distance between these permeable bulkheads was 14.74 ft. (176.9 in.) Water from the University water supply passed through a sand filter before it flowed into the headwater pool where the water level was maintained at a constant elevation by an adjustable overflow. A similar overflow was provided at the tailwater end. Samples of water which flowed through the sand prisms and tailwater overflow were collected after conditions had become steady, weighed, and timed to determine the rate of flow during each test.

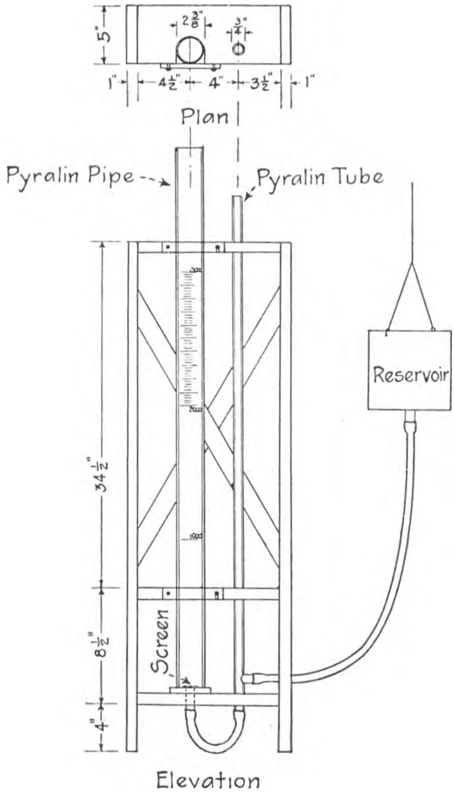

FIG. 2. SKETCH OF CAPILLARY RISE APPARATUS.

(b) Capillarimeter

The apparatus shown in Fig. 2 consisted of two pyralin tubes held vertically by a wooden frame and connected in parallel with a small reservoir. The large tube was 2 3/8 in. in diameter and 4 ft. long. A sheet of pyralin with a 3/8 in. hole in the middle, covered on one side with a fine screen, was attached to the bottom of the tube and connected by a nipple and rubber tubing to the smaller tube and reservoir as shown. The larger tube was calibrated volumetrically over a range of 3,000 cc. and suitably graduated.

(c) Small Flume

Fig. 3 shows the small flume which was used in observing directly certain details of pressure and velocity distributions as water flowed laterally through a prism of sand. This flume was 3 ft. 5 in. long,

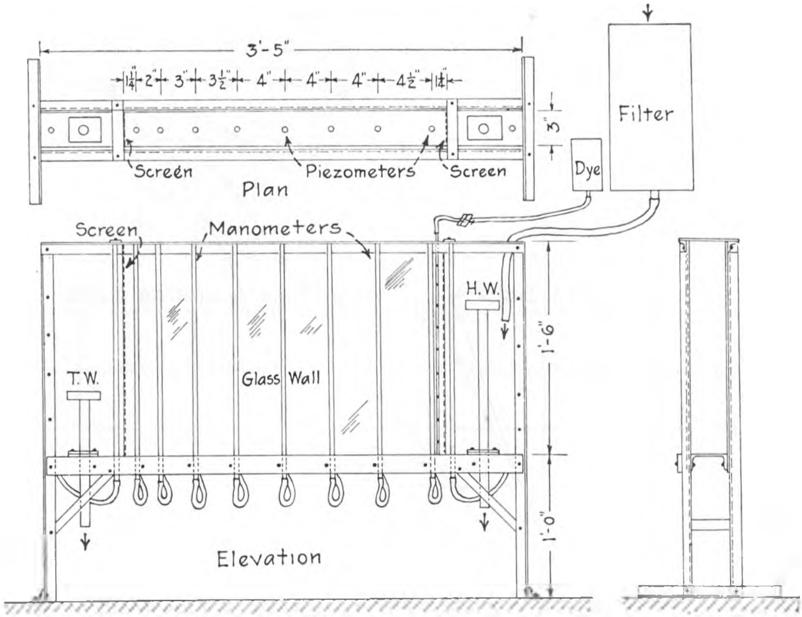

FIG. 3. SKETCH OF APPARATUS—SMALL GLASS FLUME.

18 in. high, and 3 $1/16$ in. wide. It was constructed of steel and sheet metal with one side wall of $1/4$-in. plate glass. The sand prism was confined between two fine screen partitions 27$1/2$ in. apart. Headwater and tailwater pools were maintained at desired elevations by adjustable overflows whose discharge pipes extended through glands in the floor of the flume.

Ten piezometer openings $3/16$ in. in diameter were drilled in the bottom of the flume and covered with fine screen wire. The spacing of piezometers is shown in Fig. 3. Each piezometer nipple was connected to a manometer by rubber tubing.

Before entering the headwater pool of the flume, the water passed through a sand filter as indicated in the sketch.

The device for distributing dye through the sand sample consisted of a $1/8$ in. brass tube sealed at the bottom and drilled with $1/16$ in. holes at 2 in. centers. A short section of fine capillary tube was inserted and soldered in each hole.

5. *Material.*—Commercial washed sand from the Iowa River at Iowa City was used in the experiments. Flow tests were made with

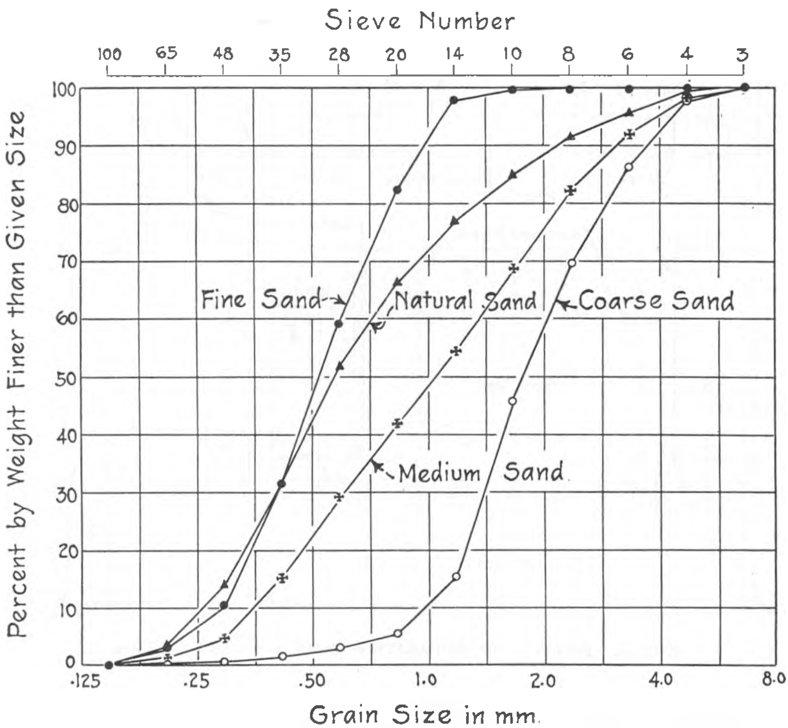

FIG. 4. MECHANICAL ANALYSIS OF SAND.

three gradations of sand which were arbitrarily designated as coarse, fine and natural sand. Capillarity tests were made with these three gradations and also with a fourth mixture which has been designated medium sand. The mechanical analyses of the materials tested are shown in Fig. 4.

The coarse sand was sieved from the pit-run sand by a motor-driven rotary sieve with a 14-mesh screen. The material which passed the sieve was designated as fine sand and that retained on the sieve was designated as coarse sand. The pit-run sand as delivered from the stock pile was designated as natural sand.

The specific gravity of five samples of each material determined by standard methods was 2.62 for the coarse sand and 2.63 for the fine and natural sands.

After the tests of each sand had been completed in the large flume, four or five sand cores were taken to determine the porosity in place. A brass cylinder 6.15 in. in diameter and 5.86 in. long was forced into the sand carefully to avoid disturbing the sample. Porosities determined on the basis of specific gravity and oven-dry weight of the coarse sample were 39.4 ± 0.3 per cent for the coarse material, 39.2 ± 0.2 per cent for the fine sand, and 37.0 ± 0.0 per cent for the natural sand.

6. *Procedure.*—The laboratory investigations may be divided into three major parts: (a) tests in the large flume to observe the flow of water through three gradations of sand and to observe piezometric groundwater profiles; (b) tests to determine the capillary rise of water in granular materials as a function of grain size, porosity, and gradation of materials; and (c) tests in the small glass-walled flume to determine directly groundwater profiles and corresponding piezometer pressures measured at the bottom of the flume, velocity distributions through the body of the sand prisms, and movement of water in the capillary fringe.

(a) Tests in the Large Flume

The flume was first filled about one-third full of water and a layer of sand was spread uniformly to a depth of about six inches. This layer was then rodded with a ½-in. steel rod in the manner of rodding a mixture of concrete. Another 6-in. layer of sand was placed under water and rodded in the same manner. The process was repeated until the flume was filled with sand to a desired depth, all material being placed under water as indicated.

The sand was allowed to stand under a stream of running water for four days before the tests were begun. Then the flume was filled two-thirds full of water and allowed to stand overnight prior to checking all manometer readings.

At the beginning of each test the inlet and outlet water surfaces were fixed by adjusting the corresponding overflow pipes. Water was allowed to run through the sand overnight and the following morning the water surfaces in the manometer tubes were observed and recorded. Water temperatures were measured in the inlet reservoir, the outlet reservoir, and at three points equally spaced along the length of the sand prism.

The water which flowed through the outlet overflow pipes was collected in a bucket resting on a small platform scales and the times required for a discharge of 25 lbs. through the coarse sand, 10 lbs. through the fine sand, and 5 lbs. through the natural sand were recorded by means of a stop watch. The discharge under each adjustment of heads was measured five or six times in the same manner and the mean rate of flow was recorded.

Both headwater and tailwater depths were varied systematically in 2 in. increments so that headwater depths ranged from 10 in. to 26 in. and tailwater depths from 6 in. to 24 in.

For each of the three sands tested in the large flume 54 piezometer profiles, rates of flow, and sets of temperature measurements were observed and recorded. By mixing hot and cold water in the supply the temperature of the water was maintained at approximately 24 degrees centigrade throughout most of the tests.

(b) Tests in the Capillarimeter

The purpose of these tests was to determine the capillary rise in the four materials tested as a function of grain size, gradation, and porosity. The sand was first heated to dryness and weighed. Then it was poured slowly and carefully into the larger tube of the capillarimeter. The bulk volume of sand in the tube was recorded as indicated by the graduations and the porosity was computed by standard methods. The water reservoir, lowered to a position near the bottom of the sand tube, was filled with water. The reservoir was then raised to a position about 12 in. above the bottom of the sand and allowed to remain in that position three hours or more. The water level in the manometer tube, the maximum and minimum capillary rise in the sand, and the volume of the sand column were then measured. After these observations had been recorded the water reservoir was raised to a new position which was usually five to eight inches above its previous elevation. After three or four hours a similar set of readings was recorded and the procedure was repeated until data had been obtained for four positions of the reservoir for each porosity. Static water pressures above the bottom of the sand column ranged from a minimum of about 5 in. to a maximum of about 38 in. in the capillarity tests.

After the first series of tests with each material, porosities were changed by either of two methods. In one the material tested was replaced by another dry sample of equal weight taken from the same stock pile. Variations in porosity were obtained by tapping the tube lightly until the bulk volume of material in the sand tube corresponded to the porosity desired. Four sets of observations were then made with this material while the sand used in the first test was dried for use in the third group of tests. Thus the two samples of sand were used alternately until the minimum porosity had been obtained by successive consolidations.

In the other method the sample was not removed from the apparatus between successive groups of tests. The porosity was changed by raising the water reservoir until the entire column of sand was submerged. Then the tube was tapped lightly until the bulk volume of sand had been reduced slightly and a new porosity was observed. The water was drained for an hour and the tests were continued as before. The second method was evidently simpler but the entire sand column remained moist and the capillary fringe was not so clearly defined as in a sand column whose upper layers were dry. However, the general outline of the capillary fringe could be observed with the aid of a mirror—the reflected light from the mirror making it possible to distinguish between the voids filled with water and those filled with air.

Both methods were checked on the same material at the same porosity. The mean difference in capillary rise observed by the two methods was less than ½ in. which was smaller than the differences in readings by each method itself.

Porosities for these tests ranged from 43 to 34 per cent for the coarse sand, from 42 to 34 per cent for the fine sand, from 40 to 32 per cent for the natural sand, and from 40 to 32 per cent for the medium sand.

Finally observations were made of the capillary rise as a function of time for the natural sand. The tests indicated that the rate of rise was very much reduced after the first two hours, and that the rise after three or four hours was about 90 per cent of that which had occurred after 16 days.

(c) Tests in the Small Flume

The procedure was essentially similar to that described for the large flume except that temperatures were observed only in the inlet and outlet chambers, and the quantities of seepage flow through the sand prisms were measured by means of a graduated cylinder and a stop watch.

In addition to observations of seepage flow, temperature, and piezometric pressure, the upper fringe of the capillary zone and the path and velocity along flow lines in the sand were observed by introducing a dye at the inlet end of the sand prisms. Four kinds of dyes were used in the tests: laundry blue, fluorescein, fuchsin, and red food color. Of these dyes the red food color was the most satisfactory. It produced a distinctive red color which was readily washed away by clear water without leaving traces in the sand or on the glass. The velocity distribution, the lines of flow, and the limits of the capillary fringe were observed along with the other measurements.

After the seepage flow through the sand had become steady the dye was introduced into the manifold tube. When the streaks of dye appeared, the stop watch was started. From time to time the positions of the front of the colored streamers were marked on the glass with a glass-marking pencil. These flow lines were then traced on cross-section paper and used as a basis for analyzing flow through the small sand prisms.

After the colored front was traced through the prism the supply of dye was shut off and the flow lines were soon washed away by the clear water which passed through the sand. The dye, however, formed a red margin at the upper surface of the flowing water. This was evidently the upper boundary of the capillary fringe and clearly defined the upper zone of flow through the material. The elevations of points on this line were finally measured at sections corresponding to those of the manometers.

Summary and Analysis of Data

7. *Flow Tests in Large Flume.*—Figs. 5, 6, and 7 summarize the tests conducted in the large flume on coarse, fine, and natural sand, respectively. Ordinates show depths of water in the headwater pool and abscissas show depths in the tailwater pool—both measured in inches above the bottom of the flume as datum. The figures adjacent to the plotted points are observed rates of flow through the sand prism in cubic feet per day corrected to a temperature of 24 degrees C. (75 deg. F.). Corrections for temperature were based on the assumption that the rate of flow varied inversely as the coefficient of viscosity.

Fig. 8 is representative of the nomographic charts which were constructed[2] on the basis of Figs. 5, 6, and 7. The three scales represent respectively the headwater depth in inches, the tailwater depth in inches, and the seepage flow in cubic feet per day. Any straight line intersecting the three scales of the chart connects

[2] For a discussion of methods of constructing nomographic charts from empirical curves see Chapter 8, "The Construction of Nomographic Charts," by F. T. Mavis. International Textbook Co., 1939.

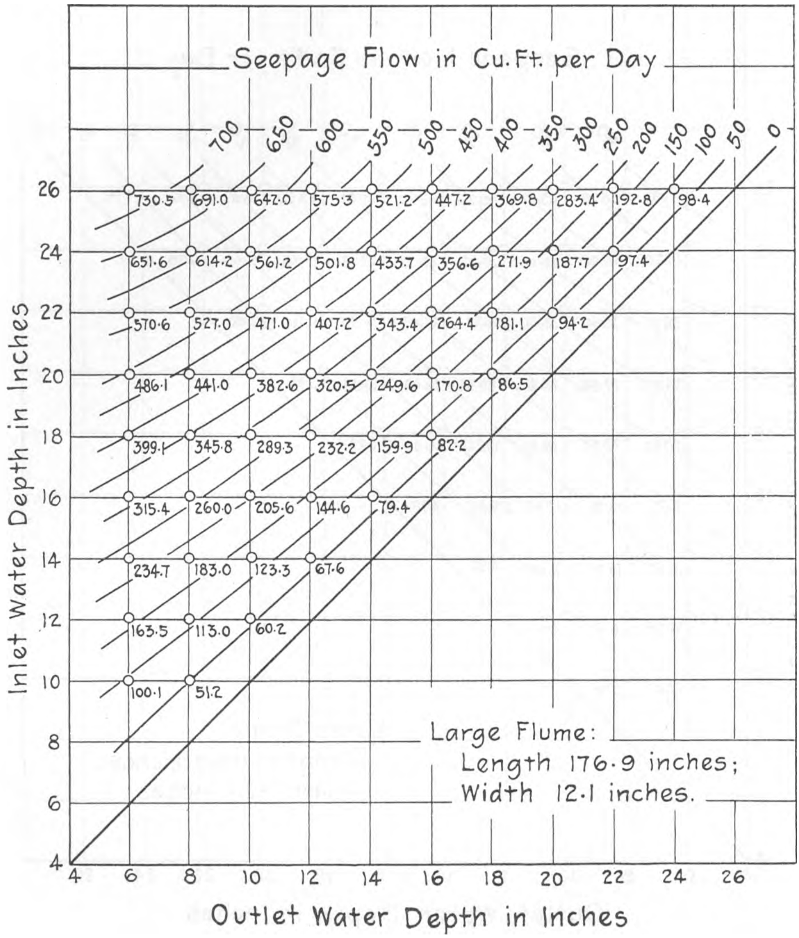

FIG. 5. SUMMARY OF SEEPAGE OBSERVATIONS—COARSE SAND.

values of the variables which are consistent with the observations. The data are generalized as a nomographic chart rather than as an empirical equation. The chart is a convenient tool of computation whose limiting range of variables is an integral part of itself. The nomograph is less likely to tempt one to extrapolate variables beyond assigned limits than an empirical equation which is too often separated from its assigned range of validity. An empirical

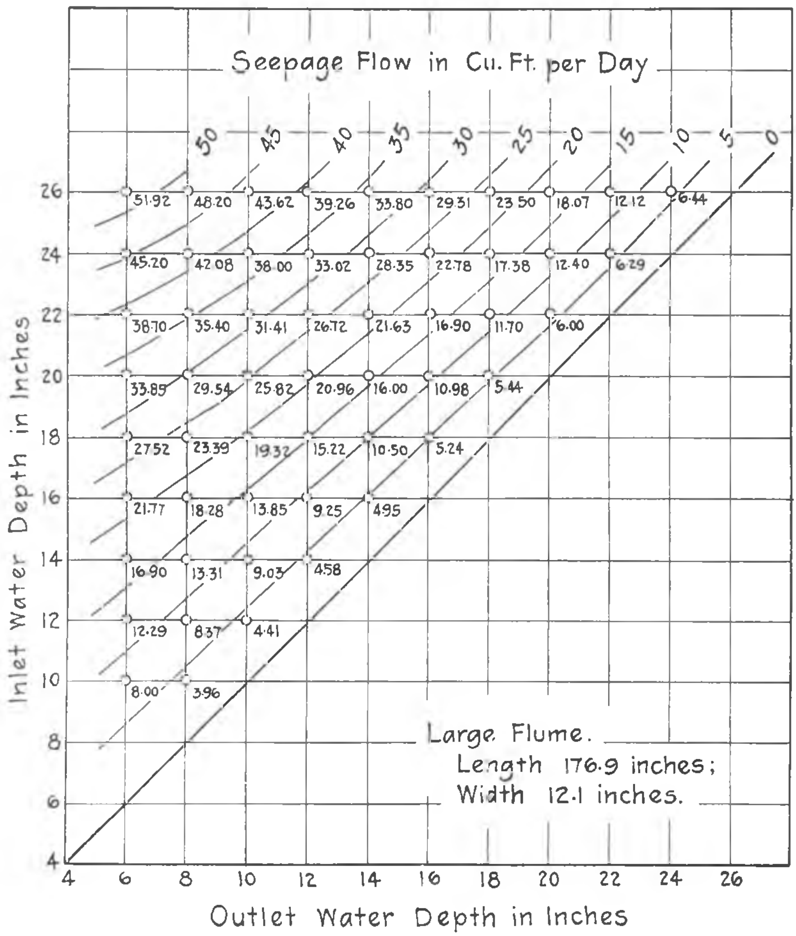

FIG. 6. SUMMARY OF SEEPAGE OBSERVATIONS—FINE SAND.

equation could easily be derived from the geometry of the nomograph, however.

8. *Piezometer Profiles in Large Flume.*—The hydraulic grade lines indicated by the piezometers connected near the bottom of the flume (the piezometer profiles) were independent of the grain size of materials used in the test. The mean diameter of the coarse sand was three times that of the fine sand, yet the piezometer profiles for given headwater and tailwater depths were identical.

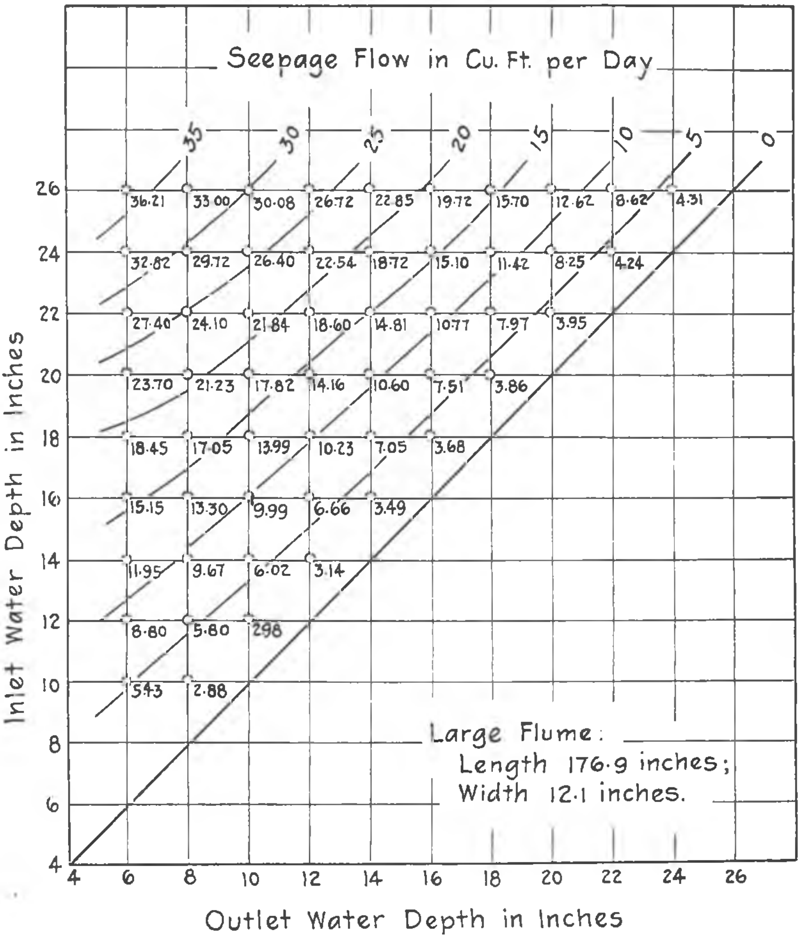

FIG. 7. SUMMARY OF SEEPAGE OBSERVATIONS—NATURAL SAND.

The piezometer profile was not a parabola as indicated by Dupuit's formula[3]

$$\frac{H_1^2 - y^2}{H_1^2 - H_2^2} = \frac{x}{L} \tag{1}$$

in which

H_1 = headwater depth above impervious datum.
H_2 = tailwater depth above impervious datum.
L = length of pervious prism.

3 J. DUPUIT, "Etudes theoriques et pratiques sur le mouvement des eaux," p. 236 (1863).

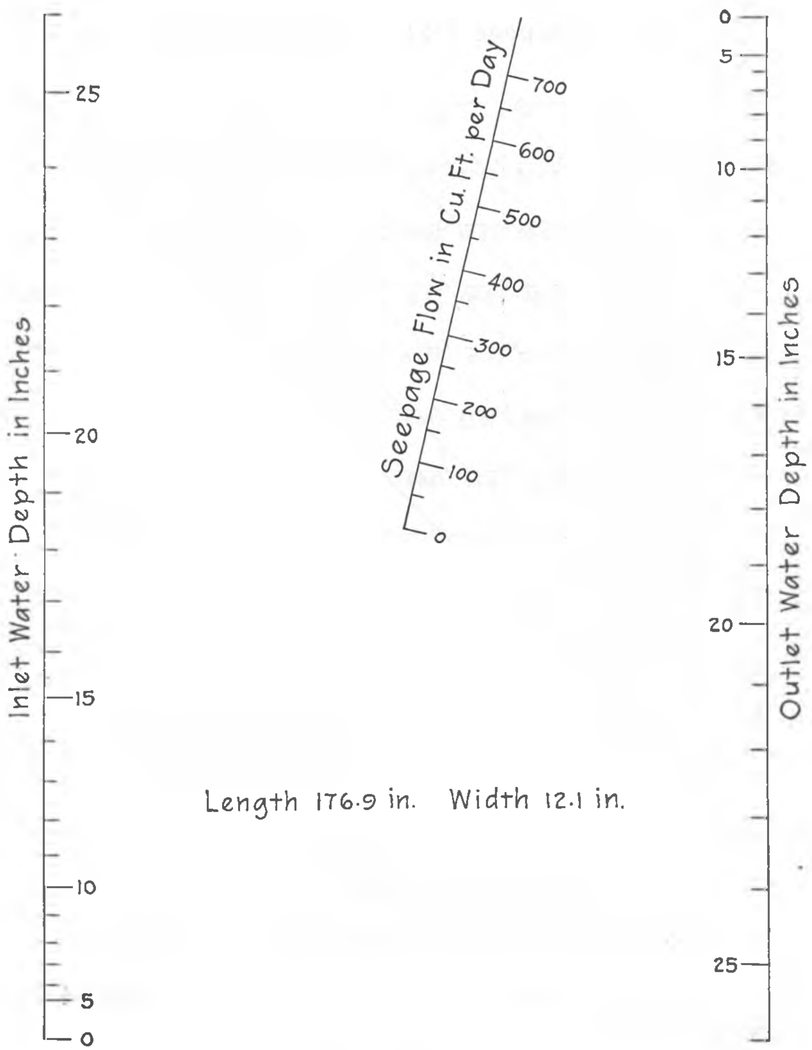

FIG. 8. ANALYSIS OF SEEPAGE OBSERVATIONS—COARSE SAND.

x, y = co-ordinates of a point on the hydraulic grade line. In Fig. 9 the observed piezometric profiles are compared with the parabolic profiles corresponding to Dupuit's formula.

An analysis of the data showed that the observed piezometric profiles were substantially in agreement with the empirical formula

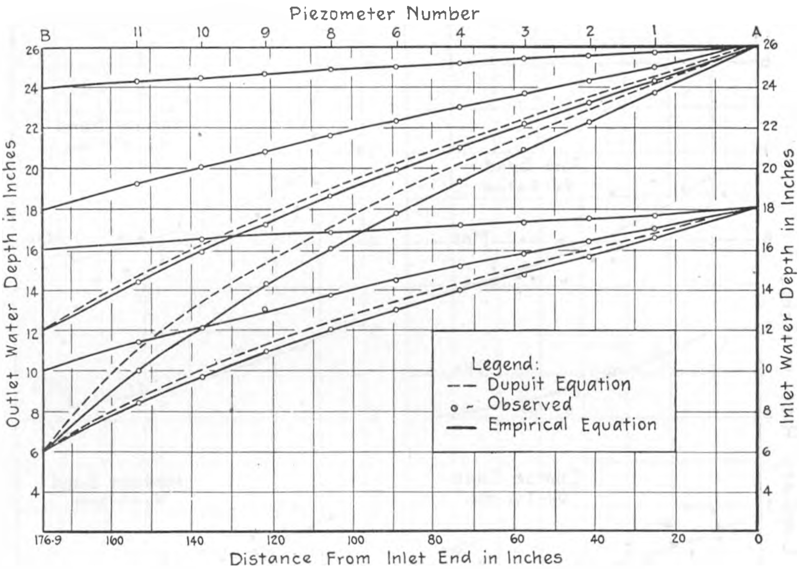

FIG. 9. PRESSURE DISTRIBUTION.

$$\frac{H_1^2 - y^2}{H_1^2 - H_2^2} = \left(\frac{x}{L}\right)^n \tag{2}$$

in which

$$n = \frac{1}{6}(5 + H_2/H_1) \tag{3}$$

Curves corresponding to Equation (2) are plotted in Fig. 9.

9. *Capillary Rise in Sand.*—The height to which water will rise in sand by capillarity depends on the size of the pores between the grains, the characteristics of the sand, and the surface tension of the water. The surface tension is a function of water temperature. The capillary rise varies directly with the surface tension of the water, and the wetted perimeter of the pores, and inversely as the cross-sectional area of the pores and the unit weight of water.

For two geometrically similar aggregations of grains arranged in the same way the mean diameter of the sand grains is directly proportional to the linear dimension of the pores. The absolute size of pores is small in fine sand and large in coarse sand, but both materials have the same porosity if they are geometrically similar. The absolute volume of pore space between adjacent grains

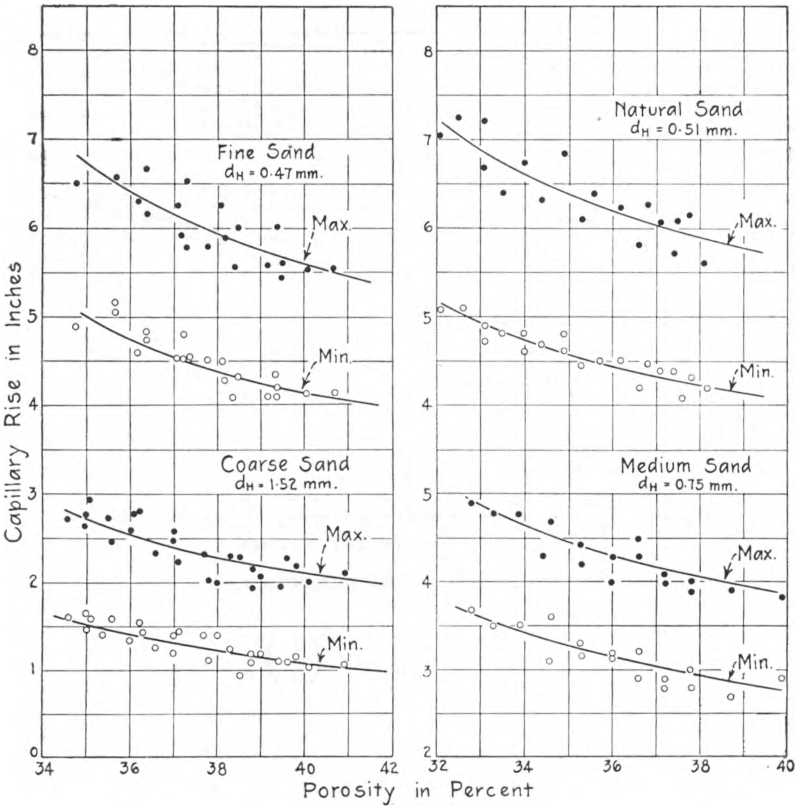

FIG. 10. CAPILLARY RISE IN SAND.

varies with the cube of grain size and the cross-sectional area of this interstitial space varies with the square of the grain size.

Fig. 10 shows a summary of the tests to determine the capillary rise in sand as a function of porosity for the four sands whose mechanical analyses are shown in Fig. 4. Ordinates show the rise in inches of the upper (max.) and lower (min.) fringes of the capillary zone above a static water level, and abscissas show porosities in percentages.

These data have been analyzed on a semi-rational basis assuming the capillary rise, h, in inches, varies inversely as the harmonic mean grain size, d_H, in millimeters, and some power of the porosity factor $(1-P)/P$, where P is the porosity ratio. Fig. 11 shows the analysis by nomographic chart. The points plotted in the middle

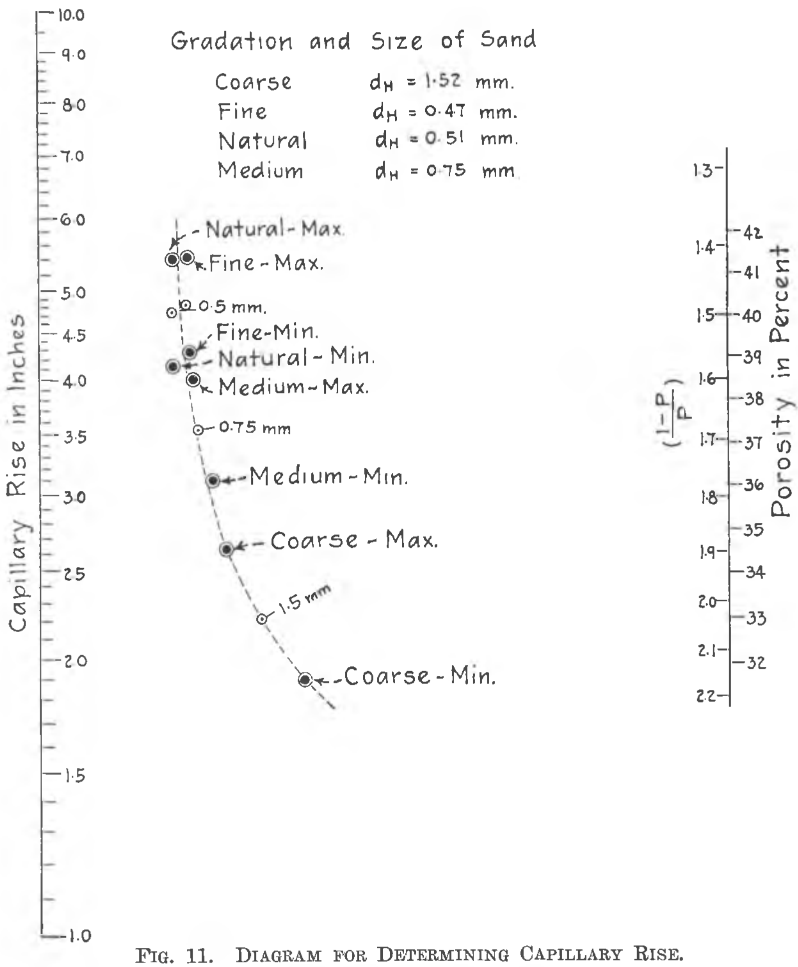

FIG. 11. DIAGRAM FOR DETERMINING CAPILLARY RISE.

field represent maximum, minimum or mean capillary rise curves for each material tested. Straight lines through any one of these points intersects the scales of capillary rise and porosity at values which correspond to points on the corresponding curve of Fig. 10.

Further observations are needed to establish a generally valid relationship. These tests suggest, however, that h_{max}, the maximum capillary rise in sand (in inches) may be represented approximately by the formula

$$h_{\max} = \frac{2.2}{d_H}\left(\frac{1-P}{P}\right)^{2/3} \tag{4}$$

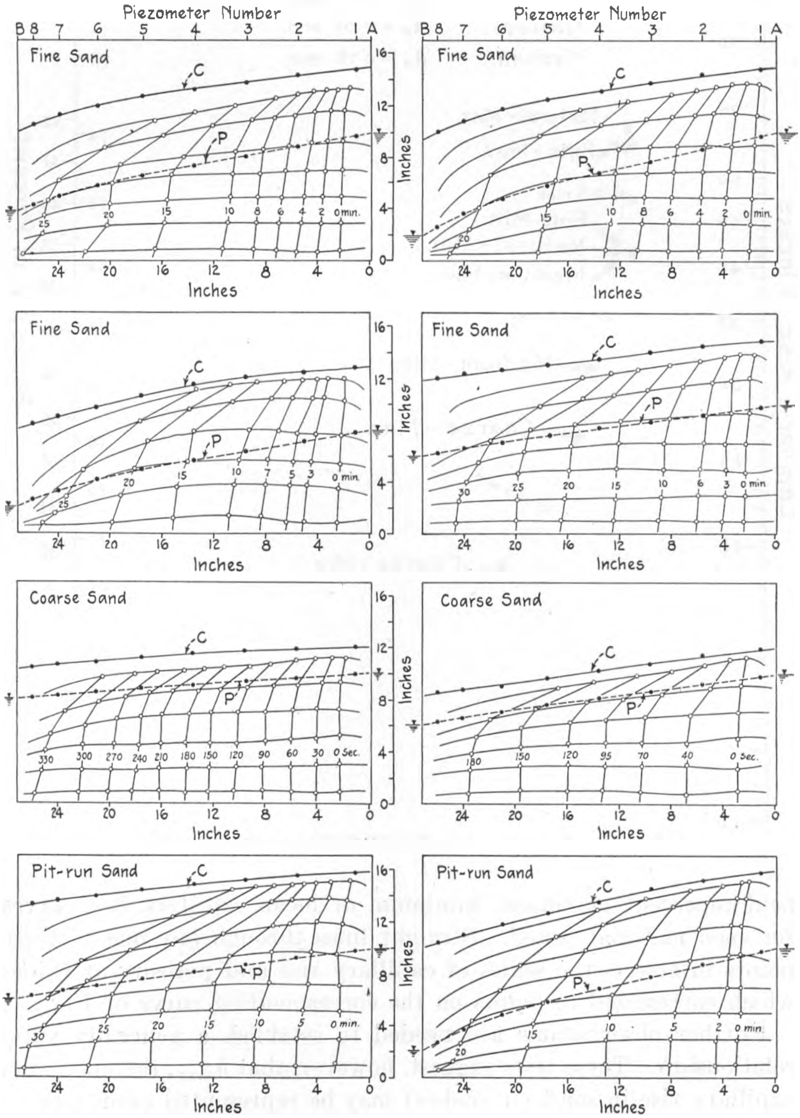

FIG. 12. OBSERVED STREAM PATHS AND SIMULTANEOUS POSITIONS OF DYE FRONTS.

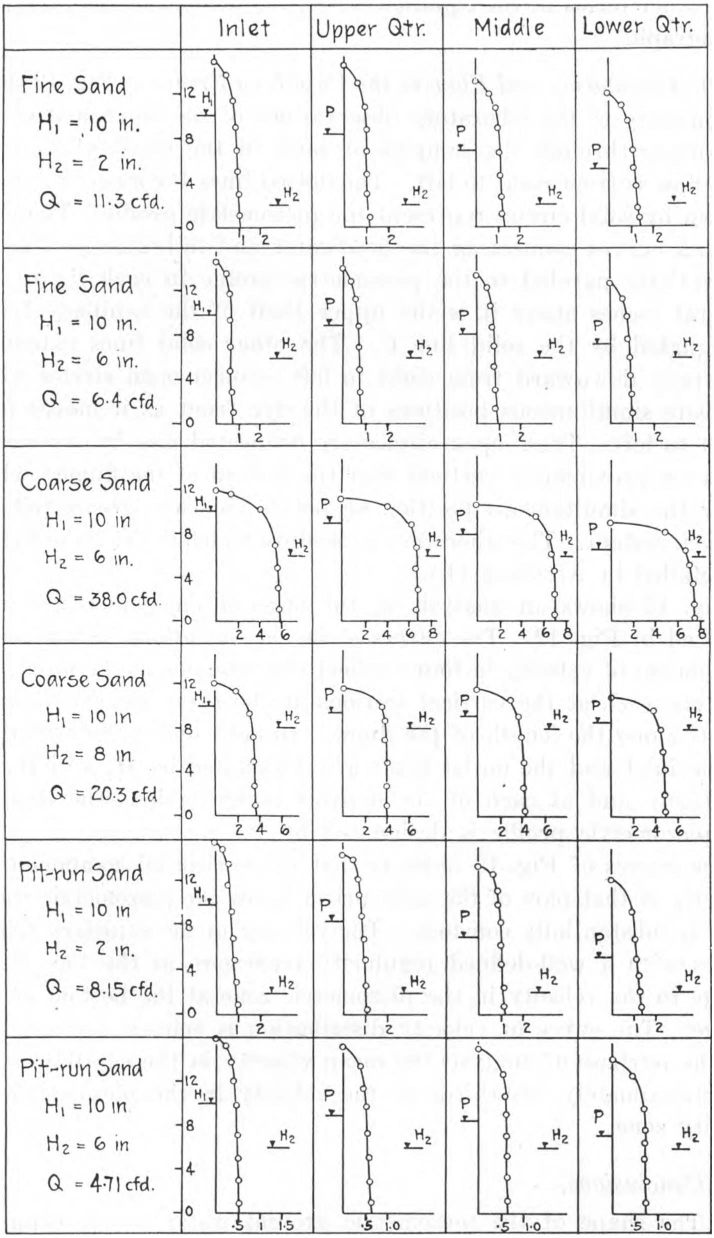

FIG. 13. TYPICAL VELOCITY DISTRIBUTION CURVES—LATERAL FLOW IN SMALL FLUME.

The other terms in the equation have been defined in the preceding paragraph.

10. *Percolation and Flow in the Capillary Fringe.*—Fig. 12 shows a summary of the laboratory observations of the movement of dye streamers through the samples of sand in the small glass flume. The flow is from right to left. The dotted lines *P* connecting points shown by solid circles represent the piezometric profile. These are smooth curves connecting the headwater and tailwater pool levels. Essentially parallel to the piezometric profile in each figure and several inches above it is the upper limit of the capillary fringe designated by the solid line *C*. The other solid lines extending generally downward from right to left connect open circles which indicate simultaneous positions of the dye front as it moves from right to left. These open circles are connected also by a series of lines—approximately vertical near the bottom of the flume—which show the simultaneous position of points on each stream path at a given instant. The laboratory procedure which led to these figures is detailed in Article 6 (b).

Fig. 13 shows an analysis of the observations which are summarized in Fig. 12. The curves show the variations in horizontal component of velocity in four vertical sections: one at the inlet face, and one each at the vertical sections at the three interior quarter points along the length of the flume. In each figure the elevations of the inlet and the outlet pools are designated by H_1 and H_2 respectively and at each of the quarter point sections the level of the piezometric profile is designated by *P*.

The curves of Fig. 13 indicate that the horizontal component of velocity in that part of the sand prism below the piezometric water level is substantially constant. The velocity in the capillary fringe varies with a well-defined regularity from zero at the top of the fringe to the velocity in the piezometric zone at the bottom of the fringe. The curve of velocity distribution is convex upward and for the purpose of analysis the mean velocity in the capillary zone is approximately two-thirds of the velocity in the piezometric or gravity zone.

11. *Conclusions.*—

1. The shape of the piezometric ground water profile connecting two fixed points in a sand prism for lateral seepage flow is independent of the gradation of the material.

2. The water in the capillary fringe moves with the gravity water in the main body of a permeable material and its average velocity is approximately two-thirds the velocity of the gravity water. This movement cannot be overlooked in model studies though it may have little significance in field practice.

3. The capillary rise of water in sand as indicated by these tests is given approximately by

$$h = \frac{2.2}{d_H}\left(\frac{1-P}{P}\right)^{2/3}$$

in which

h = capillary rise in sand in inches.
P = porosity of sample.
d_H = harmonic mean diameter of sand grains in millimeters.

4. The following modification of Dupuit's formula is in substantial agreement with laboratory observations of piezometric profiles in the large flume:

$$\frac{H_1^2 - y^2}{H_1^2 - H_2^2} = \left(\frac{x}{L}\right)^n$$

in which

H_1 = headwater depth.
H_2 = tailwater depth.
L = horizontal length of sand prism.
x and y = co-ordinates of points on the piezometric profile measured from the bottom of the tailwater pool.

$$n = \frac{1}{6}\left(5 + \frac{H_2}{H_1}\right).$$

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